Pinpointing the TeV gamma-ray emission region in M87 using TeV and 43 GHz radio monitoring

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The TeV radio galaxy M87 is the first radio galaxy detected in the TeV regime. The structure of its jet, which is not pointing towards our line of sight, is spatially resolved in X-ray (by Chandra), optical and radio observations. In 2008, the three main Atmospheric Cherenkov Telescope observatories VERITAS, MAGIC and H.E.S.S. coordinated their observations in a joint campaign from January to May with a total observation time of approx. 120 hours. In February, strong and rapid day-scale TeV flares were detected. VLBA monitoring observations during the same period showed that the 43 GHz radio flux density of the unresolved core began to rise at the time of the TeV flares and eventually reached levels above any previously seen with VLBI. New jet components appeared during the flare. The localization accuracy of the TeV instruments of many arcseconds, even for strong sources, is inadequate to constrain the origin of the emission in the inner jets of AGNs. For M87, with a 6 billion solar mass black hole and a distance of 16.7 Mpc, the VLBA resolution instead corresponds to 30 by 60 Schwarzschild radii. This is starting to resolve the jet collimation region. The temporal coincidence of the TeV and radio flares indicates that they are related and provides the first direct evidence that the TeV radiation from this source is produced within a few tens of R_S of the radio core, thought to be coincident to within the VLBA resolution with the black hole.

1. M 87 AS A UNIQUE LABORATORY FOR BLAZAR ASTROPHYSICS

Active galactic nuclei (AGN) are extreme extragalactic objects showing core-dominated emission (broadband continuum ranging from radio to X-ray energies) and strong variability on different timescales. A supermassive black hole (in the center of the AGN) surrounded by an accretion disk is believed to power the relativistic plasma outflows (jets) which are found in many AGN. More than 32 AGN have been found to emit VHE γ-rays (E>100 GeV).[1] The size of the VHE γ-ray emission region can generally be constrained by the time scale of the observed flux variability [1, 2] but its location remains unknown.

[1]See, e.g., `http://www.mpp.mpg.de/~rwagner/sources/`

The giant radio galaxy M 87 is located at a distance of 16.7 Mpc (50 million light years) in the Virgo cluster of galaxies [3]. The angle between the plasma jet in M 87 and the line of sight is estimated to lie between $20° - 40°$ [4, 5]. With its proximity, its bright and well resolved jet, and its very massive black hole with $(6.0 \pm 0.5) \times 10^9\,\mathrm{M}_\odot$ [6], M 87 provides an excellent opportunity to study the inner structures of the jet, which are expected to scale with the gravitational radius of the black hole. Substructures of the jet are resolved in the X-ray, optical and radio wavebands [7] and high-frequency radio very long baseline interferometry (VLBI) observations with sub-milliarcsecond (mas) resolution are starting to probe the collimation region of the jet [8]. This makes M 87 a unique laboratory in which to study relativistic jet physics in connection with the mechanisms of VHE γ-ray emission in AGN.

VLBI observations of the M 87 inner jet show a

well resolved, edge-brightened structure extending to within 0.5 mas (0.04 pc or 70 Schwarzschild radii R_S) of the core. Closer to the core, the jet has a wide opening angle suggesting that this is the collimation region [8]. Along the jet, monitoring observations show both near-stationary components [9] (pc-scale) and features that move at apparent superluminal speeds [10, 11] (100 pc-scale). The presence of superluminal motions and the strong asymmetry of the jet brightness indicate that the jet flow is relativistic. The near-stationary components could be related to shocks or instabilities that can be either stationary or move more slowly than the bulk flow.

2. TEN YEARS OF VHE GAMMA-RAY OBSERVATIONS OF M 87

Currently, there are more than 30 extragalactic objects – all belonging to the class of AGN – that have been established as VHE γ-ray emitters by ground-based imaging atmospheric Cherenkov telescopes (IACTs), such as H.E.S.S. [12], MAGIC [13] and VERITAS [14]. So far, all of them except the radio galaxies M 87, Centaurus A [15], and possibly 3C 66B [16], as well as the starburst galaxies M82 [17] and NGC 253 [18], belong to the class of blazars (exhibiting a plasma jet pointing closely to our line of sight).

A first indication of VHE γ-ray emission ($> 4\,\sigma$) from the direction of M 87 in 1998/9 was reported by HEGRA [19]. The VHE γ-ray emission was confirmed by H.E.S.S. [2], establishing M 87 as the first non-blazar extragalactic VHE γ-ray source. The reported day-scale variability strongly constrains the size of the γ-ray emission region. VERITAS detected M 87 in 2007 [20] but with no variability. Recently, the short-term variability in M87 was confirmed by MAGIC in a strong VHE γ-ray outburst [21]. The yearly averaged VHE γ-ray light curve of M 87 for the past 10 years is shown in Fig. 1. The measured flux variability rules out large-scale emission from dark matter annihilation [22], or cosmic-ray interactions [23]. Leptonic [24, 25] and hadronic [26] jet emission models have been proposed to explain the TeV emission. The location of the VHE γ-ray emission is still unknown, but the nucleus [27], the inner jet [24, 25, 26, 28] or larger structures in the jet [29] have been proposed as possible sites. The 2005 VHE γ-ray flare (H.E.S.S.) was detected during an exceptional, several years lasting X-ray outburst of the innermost knot in the jet "HST-1" [30], whereas the recent VHE γ-ray flaring activity (reported here) occurred during an X-ray low state of HST-1 (see Fig. 1). In this paper we report on a joint VHE observation campaign of M 87 performed by H.E.S.S., MAGIC and VERITAS in 2008.

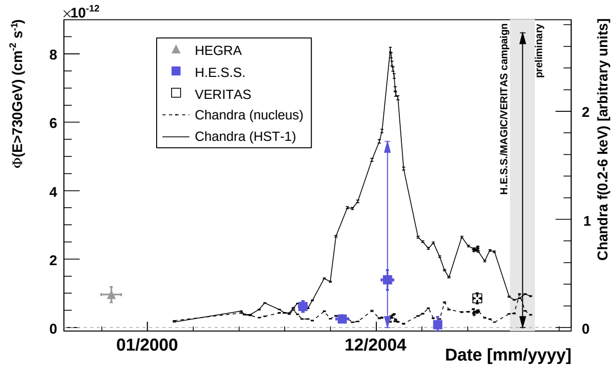

Figure 1: The yearly averaged VHE γ-ray light curve $\Phi(E > 730\,\mathrm{GeV})$ of M 87, covering the 10-year period from 1998-2008. The data points are taken from [2, 19, 20, 21]. Vertical arrows indicate the measured flux ranges for the given period (if variable emission was found). Strong variabilities ($<$ 2 days flux doubling times) were measured in γ-rays in 2005 and 2008. The Chandra X-ray light curves of the nucleus and HST-1 are also shown [30].

3. THE 2008 CAMPAIGN ON M87

3.1. Joint H.E.S.S./MAGIC/VERITAS VHE observations

IACTs measure very high energy ($E > 100$ GeV) γ-rays. The angular resolution of $\sim 0.1^\circ$ of IACTs does not allow to resolve the M 87 jet, but the time scale of the VHE flux variability constrains the size of the emission region, while flux correlations with observations at other wavelengths may enable conclusions on the location of the VHE γ-ray source. The current generation of instruments requires less than 10 h for the detection of a faint source with a flux level of a few percent of the Crab nebula flux. For a variable VHE γ-ray source like M 87, a joint observation strategy as well as combining the results from several IACT experiments (and observations at other wavelengths) can substantially improve the scientific output (e.g. [31]). Coordinated observations with the VHE instruments H.E.S.S., MAGIC, and VERITAS result in:

- an extended energy range by combining data sets taken under different zenith angles
- an extended visibility during one night, because the visibility of any given celestial object depends on the longitude of the experimental site
- an improved overall exposure and homogeneous coverage of the source
- alerts and direct follow-up observations in case of high flux states.

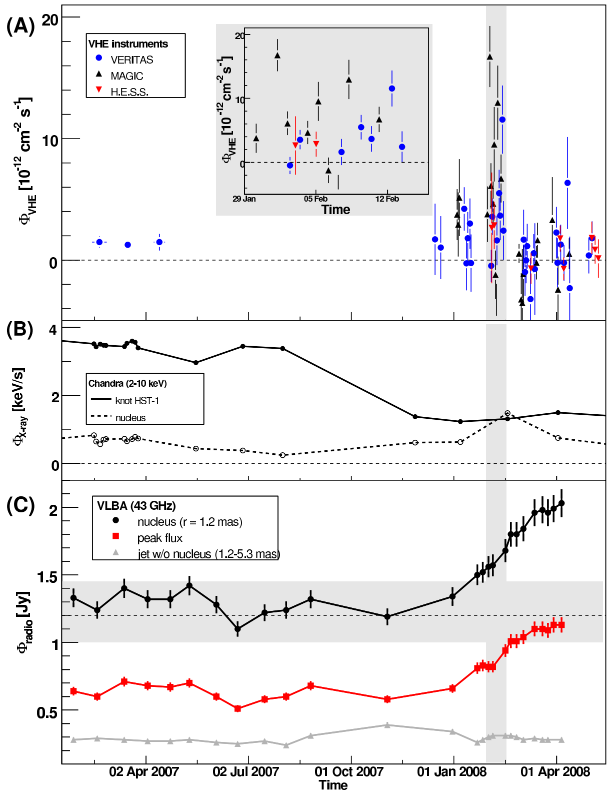

Figure 2: *(A)*: the night-by-night averaged VHE γ-ray light curve $\Phi(E > 350\,\mathrm{GeV})$ of M 87, covering the 2008 joint campaign. Strong variability resulted in a detection of at least two flares (see the inlay for a enlarged view of the relevant period). *(B)*: Corresponding *Chandra* measurements of the core and the HST-1 knot of M87. *(C,D)*: Flux densities from the 43 GHz VLBA observations for the nucleus, the peak flux (VLBA resolution element), and the flux integrated along the jet. The shaded horizontal area indicates the range of fluxes from the nucleus before the 2008 flare. While the flux of the outer regions of the jet does not change significantly, most of the flux increase results from the region around the nucleus.

Among other AGN, the radio galaxy M 87 is part of a multi-collaboration AGN trigger agreement between H.E.S.S., MAGIC and VERITAS. In order to achieve a best possible VHE coverage (especially during Chandra X-ray observations) a closer cooperation was conducted for the 2008 observations of M 87. The collaborations agreed to have a detailed exchange/synchronization of their M 87 observation schedules. Further on, information about the status of the observations (i.e. loss of observation time due to bad weather conditions, etc.) was exchanged on a regular basis between the shift crews and the observation coordinators.

M 87 was observed by the three experiments for a total of > 120 h in 2008 ($\sim$95 h after quality selection). The amount of data resulted in an unprecedentedly good coverage with >50 nights between January and May 2008.

3.2. Chandra X-ray observations

Chandra monitoring of M 87 began in 2002 and continues to date. The angular resolution ($\approx 0.8''$) allows resolving the large-scale jet structure, and in particular to distinguish emission from the core and the innermost knot ‘HST-1’ (left panel in Fig. 3). During an observing season, M 87 is observed every $\sim$6 weeks. That sampling allows detection of 1.5 month-scale variability. The most remarkable discovery of the monitoring campaign so far has been the giant flare of HST-1 [30], which reached its maximum intensity in 2005 (Fig. 1) when the TeV emission was detected in flaring state for the first time, suggesting HST-1 as the possible origin of the VHE emission [29]. Simultaneously, a huge optical flare was detected by the Hubble Space telescope [32]. Additional observations were taken in 2007 on shorter intervals to investigate short-time variability and possible correlation with VHE emission, which was unfortunately in a quiet state at that time.

3.3. Radio: VLBA

Throughout 2007, M 87 was observed at 43 GHz with the VLBA on a regular basis roughly every three weeks [33]. In January 2008, the campaign was intensified to one observation every 5 days. The resolution of the observations is rather high with 0.21×0.43 milliarcseconds or 15×30 Schwarzschild diameters of M 87. The aim of this “movie project” was to study morphological changes of the plasma jet with time. Preliminary analysis of the first 7 months showed a fast evolving structure, somewhat reminiscent of a smoke plume, with apparent velocities of about twice the speed of light. These motions were faster than expected so the movie project was extended from January to April 2008 with a sampling interval of 5 days.

The 43 Ghz radio flux density from the unresolved core rose by 0.3 Jy (36%) while the integrated flux density from within 1.2 mas of the core rose by 0.57 Jy (32%). beginning at the time of the VHE flare and extending over at least the following two months until the VLBA monitoring project ended (Fig. 2). Beyond 1.2 mas, there was no change. The initial radio flux density increase was located in the unresolved core. The region around the core brightened as the flare progressed (Fig. 4), suggesting that new components were emerging from the core. At the end of the observations, the brightened region extended about 0.77 mas from the peak of the core implying an average apparent velocity of 1.1c, well under the approximately 2.3c seen just beyond that distance in the first half of 2007. The position of the M 87 radio peak did not

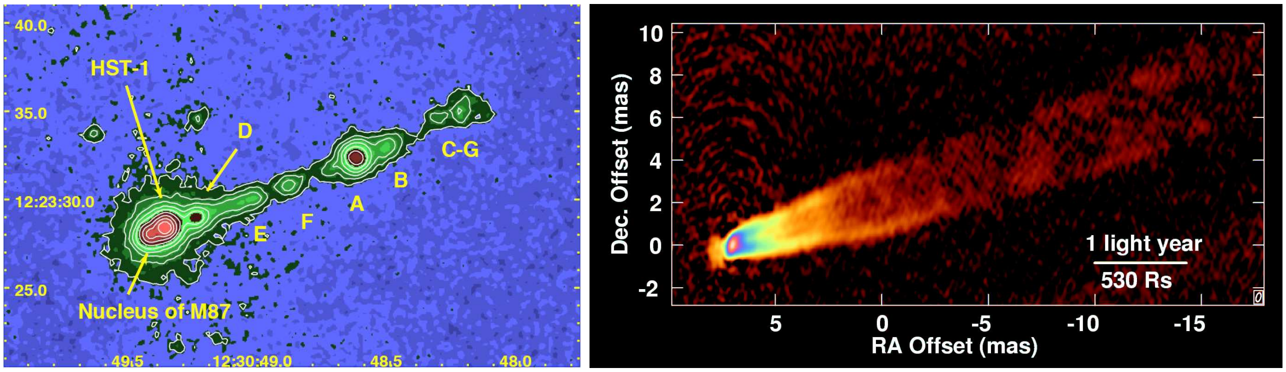

Figure 3: Image of the M 87 jet with high resolution instruments: Large-scale jet in X-ray obtained with Chandra (left). Inner jet in radio (43 GHz) obtained with VLBA (right).

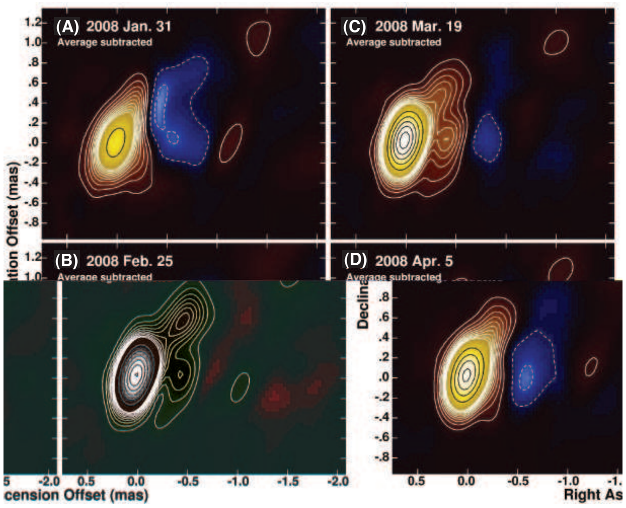

Figure 4: VLBA images of M 87 at 43 GHz. (A)-(D): Sequence of difference images for observations during the period of the radio flare. These images have had an average image subtracted in order to show the effects of the flare. The average was made from eleven observations in 2007, outside the period affected by the flare. The contours are linear with 10 (white) at intervals of 7 mJy per beam followed by the rest (black) at intervals of 70 mJy per beam; negative contours are indicated by dashed lines. The sequence shows the significant rise in the core flux density and the appearance of enhanced emission along the inner jet.

move by more than $\approx 12 R_S$ during the flare, indicating that the peak emission corresponds to the nucleus of M 87.

3.4. Results

In January 2008, the VHE γ-ray flux was measured at a slightly higher level than in 2007. MAGIC detected a strong flaring activity in February 2008 [21], which led to immediate intensified observations by all three VHE experiments. VERITAS detected another flare about one week after the MAGIC trigger. The joint 2008 VHE γ-ray light curve clearly confirms the short-term variability reported by H.E.S.S. in 2005 [2]. During the 2008 VHE flaring activity, MAGIC observed flux variability above 350 GeV on time scales as short as 1 day (at a significance level of 5.6 standard deviations). At lower energies (150 GeV to 350 GeV) the emission was found to be compatible with a constant level [21]. From March to May, M 87 was back in a quiet state.

In 2008, the X-ray and VHE γ-ray data suggested a different picture compared to the 2005 flare (Fig. 1): HST-1 was in a low state, with the flux being comparable with the X-ray flux from the core. The core, however, showed an increased X-ray flux state in February 2008, reaching a highest flux ever measured with Chandra just few days after the VHE flaring activity.

VLBA measured a continuously increasing radio flux from the region of the nucleus (r=1.2 mas) during the 2008 campaign, whereas in 2007 the flux was found to be rather stable. Individual snapshots of the inner region of the jet are shown in Fig. 4. The observed radio flux densities reached at the end of the 2008 observations, roughly 2 months after the VHE flare occurred, are larger than seen in any previous VLBI observations of M 87 at this frequency, including during the preceding 12 months of intensive monitoring, in 6 observations in 2006 and in individual observations in 1999, 2000, 2001, 2002, and 2004 [34]. This suggests that radio flares of the observed magnitude are uncommon.

Given the rare occurrence of VHE, radio and X-ray flares at very similar times as compared to their characteristic time scales, we conclude that the events are likely connected. This conclusion is supported by the joint modeling of the VHE and radio light curves (Fig. 5). The VLBI structure of the flare, along with the timing of the VHE activity, is strong evidence that the VHE emission occurred in a region small compared to the VLBA resolution. The observed pattern can be

explained by an event in the central region causing the VHE flare. The effect of synchrotron self absorption causes a delay of the observed peak radio emission since the region is not transparent at radio energies at the beginning. This will lead to a smoothed and delayed shape of the radio light curve.

M 87 is the first radio galaxy that shows evidence for a connection between simultaneous, and well sampled, radio and VHE γ-ray flux variations (which are separated in photon frequency by 16 orders of magnitude), opening a new avenue for the study of the AGN accretion and jet formation. General relativistic magneto hydrodynamic simulations indicate that jets might be launched and collimated magnetically over large spatial scales of $\approx 1000 R_S$, e.g. [35]. In the radio galaxy M 87, the VHE emission seems to originate much closer to the central region. Either it originates directly in the black hole magnetosphere assuming that the radio core is coincident with the black hole or it originates in a jet which accelerates on spatial scales smaller than $\approx 100 R_S$.

The correlation study and the implication of the 2008 results on the VHE emission models are presented in detail in [36].

4. COLLECTION OF MODELS FOR THE GAMMA-RAY EMISSION IN M87

The data collected in Fig. 5 are non-simultaneous and the models were partly published before the TeV flaring was a known characteristics of M87. (Some of them can probably be tuned to descibe the recent data). However, some qualitative statements are possible in the light of the results of the 2008 campaign, motivating future simultaneous observations.

The hadronic synchrotron proton blazar model by Reimer et al. [26] was fit only based on the HEGRA detection (1998/99). However, it seems to be hard to make it work in the Fermi energy range (very different slopes) and it also leads to a strong intrinsic cut-off at a few TeV, making it difficult to describe the hard TeV spectra consistently measured by H.E.S.S., MAGIC and VERITAS. It seems to be difficult to describe a radio/TeV connection in this model framework.

In the black hole magnetosphere model by Neronov & Aharonian [27], the TeV emission originates direct in BH vicinity. The data was fit to the H.E.S.S. 2005 flare. The fit seems to be compatible with the general shape of the Fermi regime, and it also is in the same ballpark for the radio data.

The leptonic de-accelerated inner jet model by Georganopoulos, Perlman, & Kazanas [24] was published before the H.E.S.S. 2005 flare, so it does not describe the hard TeV spectra well (strong cut-off). It might be tuned, however, to a harder flare state.

In the model by Lenain et al. [25], individual blobs in the inner jet close to the BH emit the TeV γ-rays. This model was fit to the H.E.S.S. low (2004) and high (2005) states. Only the 2004 fit (low state) is currently shown in the plot in order to declutter the plot. This model also explains the observed radio emission.

In the spine/sheath model [28] framework (Tavecchio & Ghisellini) it seems to be difficult to explain the radio data as part of this emission mechanism.

5. CONCLUSION AND OUTLOOK

The cooperation between H.E.S.S., MAGIC and VERITAS in 2008 allowed for an optimized observation strategy, which resulted in the detection and detailed measurement of a VHE γ-ray outburst from M 87. Simultaneous Chandra observations, found HST-1, the innermost knot in the jet, in a low state, while the nucleus showed increased X-ray activity. This is in contrast to the 2005 VHE γ-ray flare, where HST-1 was in an extreme high state. The radio activity in 2007–8, resolving the inner region of M87 down to some 10s Schwarzschild radii (R_S), allowed to infer the origin of the VHE γ-ray emission. A model suggesting HST-1 to be the origin of the γ-ray emission seems less likely in the light of the 2008 result. Due to its proximity and the viewing angle of the jet, M 87 is a unique laboratory for studying the connection between jet physics and the measured VHE γ-ray emission. The modest localization accuracy of the TeV instruments of many arcseconds, even for strong sources, is inadequate to constrain the origin of the emission in the inner jets of AGNs. The VLBA resolution instead corresponds to 30 by 60 R_S. This is starting to resolve the jet collimation region. The temporal coincidence of the TeV and radio flares indicates that they are related and provides the first direct evidence that the TeV radiation from this source is produced within a few tens of R_S of the radio core, thought to be coincident to within the VLBA resolution with the black hole.

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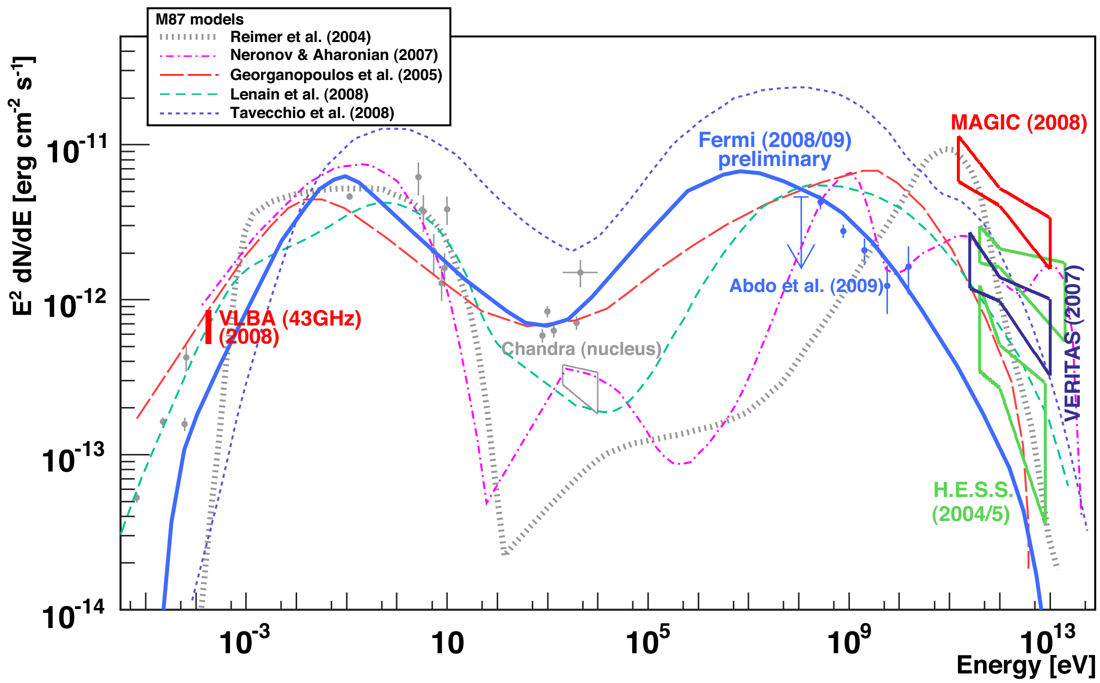

Figure 5: SED data and models for M 87. Grey points: archival radio and optical data, as well as the EGRET upper limit, taken from [25]. The vertical red line (VLBA) shows the range of radio fluxes during the 2008 flare (nucleus). Fermi data points (blue data points) and model (blue solid line) taken from [37]. The models are taken from the literature, see main text for references.

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